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14. ABSTRACT

The objective of this project is to develop tunable high efficiency resonant tunneling GaN/AlGaN multiple quantum well (MQW)-based UV photodetectors. During the grant period, more than twenty six GaN/AlGaN MQW phoptodetectors with different types of device structures and control samples have been fabricated and investigated to achieve the proposed narrow band detection, high efficiency and fast response time. The research results have been published in five refereed journals, presented at six conferences, and included in an U. S. patent application.

The major accomplishments/achievements are: (a) lateral-geometry GaN/AlGaN MQW UV photodetectors were fabricated and investigated. A narrow band spectral response of 297 nm to 352 nm and a fast response speed of 50 μs at 50 Ω load were achieved; (b) GaN/AlGaN heterojunction UV photodetectors were fabricated, and a high internal gain of $>10^3$ was observed. This achievement was reported as a "Newsbreak" on page 15 in the February, 2003 issue of "Laser Focus World"; (c) perpendicular-geometry GaN/AlGaN MQW Schottky UV photodetectors with different barrier thickness were fabricated, and the barrier-thickness dependence of the photoresponsivity was investigated. The results show that as the barrier thickness decreases, the responsivity rapidly increases in the active wavelength range; (d) GaN/AlGaN photodetector structures using p-6H-SiC as a p-type layer in p-i-n structures as well as a substrate for the growth of AlGaN materials were fabricated and investigated to overcome two major problems: low p-type doping level in AlGaN and poor quality of AlGaN epitaxy layers on sapphire substrate; (e) in order to reduce dark current and improve photodetector performance, GaN/AlGaN p-i-n detectors were grown with a SiN dislocation-blocking layer. The extremely low dark current ($\sim 1\times 10^{-13}$ A at zero bias) was observed; (f) sequential resonant tunneling in a GaN/AlGaN MQW photodetector with a SiN dislocation-blocking layer was achieved; and (g) the shallow-donor and deep-center recombination in GaN/AlGaN MQW photodetectors, and their affects on device performance were studied.

15. SUBJECT TERMS
Ultraviolet (UV) photodetector, multiple quantum well, resonant tunneling, GaN and AlGaN, photo-responsivity, response speed, internal gain, deep center.

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FINAL REPORT
For AFOSR Grant F49620-01-1-0188
(CUNY RF 4747444-00-01)
Period covered 03/01/01 – 02/28/05

Objectives

The objective of the AFOSR research project (#F49620-01-1-0188, CUNY RF # 47444-00-01) was to develop tunable high efficiency resonant tunneling GaN/AlGaN MQW-based UV photodetectors. These next generation UV photodetectors can be used in space-to-earth and space-to-space communication, homeland security, missile plume detection, combustion sensing and control for aircraft engines, optical storage, air quality monitoring, and personal UV exposure dosimetry.

Summary of Achievements

During the grant period, more than twenty six GaN/AlGaN MQW photodetectors with different types of device structures and control samples have been fabricated and investigated to achieve the proposed narrow band detection, high efficiency and fast response time. The research results have been published in five refereed journals, presented at six conferences, and included in an U. S. patent application.

The following highlights the GaN/AlGaN MQW UV photodetector structures we fabricated and investigated, and the results obtained from the studies on those MQW-based photodetector samples:

(a) The lateral-geometry back-illuminating GaN/AlGaN MQW UV photodetectors were fabricated and investigated for the study of narrow band detection. A narrow band spectral response of 297 nm to 352 nm and a fast response speed of 50 μs at 50 Ω load were achieved.[1] The tunable and selective band detection is attributed to the introduction of MQWs in the photodetector devices. To the best of our knowledge, this was the first demonstration of GaN/AlGaN MQW photodetectors.

(b) The GaN/AlGaN heterojunction UV photodetectors deposited on a c-plane sapphire substrate with a co-planar Schottky contact were fabricated for the internal gain study. A high internal gain of $>10^3$ as well as a narrow band spectral response of 365nm to 434 nm were observed for this heterojunction GaN/AlGaN photodetector.[2] This breakthrough achievement on high internal gain of the GaN/AlGaN heterojunction UV photodetectors was reported as a "Newsbreak" on page 15 in the February, 2003 issue of "Laser Focus World".

(c) The perpendicular-geometry GaN/AlGaN MQW Schottky UV photodetector samples with different barrier thickness and same well thickness were fabricated and investigated to study the barrier-thickness dependence of their photo-responsivity. The results show that as the barrier thickness decreases, the responsivity of the devices rapidly increases in the active wavelength range.[3,4] This is attributed to the enhanced probability of carrier tunneling through the thin barriers in the GaN/AlGaN MQW region. The performance of these three types of detectors was also tested under different biases. The results indicate that large electric fields can sweep out photo-generated carriers more efficiently from the active MQW region through tunneling, and almost all carriers can be transported to the collectors after a certain field is reached.[3,4]

(d) In order to overcome two major problems for making high quality p-i-n GaN/AlGaN photodetectors: low p-type doping level in AlGaN material, and poor quality of AlGaN epitaxy layers on sapphire substrate, we have designed, fabricated and tested GaN/AlGaN photodetector structures using p-type 6H-SiC as a p-type layer in p-i-n structures as well as a substrate for the growth of AlGaN layerls. The p-i-n structure for those UV photodetectors is 6H-SiC (p) - GaN/AlGaN MQWs (i) - AlGaN (n). The PL, I-V and photoresponse measurements on these samples show that the p-type doing problem was solved and the 6H-SiC (p) - GaN/AlGaN MQWs (i) - AlGaN(n) UV photodetectors were successfully operated.[5]

(e) For the purpose of reducing dark current and improving photodetector performance, a number of GaN/AlGaN p-i-n detectors were grown with SiN dislocation-blocking layers. The dark current for these photodetectors was found as low as $\sim 1\times 10^{-13}$ A at zero bias. It is only 2×10^{-12} A even at –5 V. The extremely low dark current is attributed to successful blocking of threading dislocations by SiN layer. The photoresponse measurements show that deposition of SiN dislocation-blocking layer is helpful in improving performance of GaN/AlGaN photodetectors, and this SiN layer does not distort the spectral response curve.[6]

(f) To achieve high quantum efficiency and fast response speed, we have fabricated and investigated p-GaN/i-MQW/n-AlGaN UV photodetector structures with a possible sequential resonant tunneling (SRT) under a proper bias.[7] For the GaN/AlGaN MQW photodetectors with a SiN dislocation-blocking layer, the signature of SRT was observed even at room temperature from the measured I-V curve. Due to the high quality of materials and the reduction of threading dislocations, the I-V curve of the GaN/AlGaN MQW photodetectors shows two peaks, which correspond to the resonant tunneling of electrons from the ground state E_1 of a well to the first and second excited states E_2 and E_3 of an adjacent well, respectively.

(g) Deep centers in III-Nitride materials play an important role in the performance of III-Nitride photovoltaic devices. We have studied shallow-donor and deep-center recombination in GaN/AlGaN MQW photodetectors, and their affects on device performance using transient photocapacitance (TPC) technique. The long decay time of GaN photodetectors is found to arise from donor-acceptor pairs in GaN. A transient photocapacitance model has been developed and used to explain the optical power dependence of TPC traces measured for a GaN/AlGaN MQW Schottky diode.[8]

The details of these accomplishment are described in the next section, "Accomplishments / New Finding".

Accomplishments / New finding

The following highlights our major research accomplishments and new findings during the grant period (3/1/01 – 2/28/05):

1. Growth and fabrication of different types of GaN/AlGaN MQW UV photodetectors

More than twenty six GaN/AlGaN MQW photodetectors with different types of device structures and control samples have been fabricated and studied for this research project. The samples were designed and investigated by Prof. Alfano's group at CCNY, and grown and fabricated by Prof. Morkoc's group at VCU. The type and number of the GaN/AlGaN MQW UV photodetector samples, and the studies performed on these samples are summarized in Table 1.

Table 1 GaN/AlGaN MQW UV photodetector samples fabricated and investigated during the grant period

Type of samples	Number of the samples	Studies performed
Lateral-geometry GaN/AlGaN MQW UV photodetectors and control samples	4	Narrow band spectral response and response speed
GaN/AlGaN heterojuction UV photodetectors and control samples	4	Internal gain and photoresponse band
GaN/AlGaN MQW Schottky UV photodetectors with different barrier widths, and control samples	9	Barrier thickness dependence of photo-responsivity
GaN/AlGaN MQW UV photodetectors using SiC as a p-type doping layer and substrate	2	Approaching high level p-doping for AlGaN-based p-i-n structures
GaN/AlGaN MQW UV photodetectors with a SiN dislocation-blocking layer	2	Reducing dark current and enabling sequential resonant tunneling
GaN/AlGaN MQW UV photodetectors and control samples	5	Shallow-donor and deep-center recombination, and their effect to device performance of GaN/AlGaN MQW-based photodetectors

2. Fabrication and investigation of lateral-geometry back-illuminated GaN/AlGaN MQW UV photodetectors

The layer structure of a lateral-geometry back-illuminated GaN/AlGaN MQW UV photodetector is shown in Fig.1. The GaN (4 nm)/$Al_{0.27}Ga_{0.73}N$ (7 nm) MQWs with 21 periods were deposited by MBE on a 1-μm thick $Al_{0.35}Ga_{0.65}N$ buffer layer which was epitaxied grown on a sapphire substrate. Co-planar gold ohmic contacts were made on the topside of the MQW structure with the width and spacing of 1 mm. The MQWs below the metal stripes are the active region to create photoresponse. Photocurrent is produced by lateral diffusion of photogenerated carriers from one electrode to the neighboring one.[1]

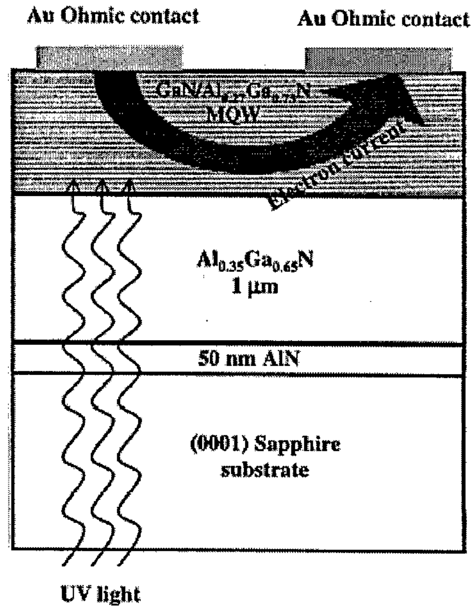

Fig.1 Schematic layer structure of a lateral-geometry back-illuminated UV photodetector based on GaN/AlGaN multiple quantum wells.

By illuminating the ohmic contact positions from the backside of the detector, a narrow band spectral response is achieved in the UV wavelength range from 297 nm to 352 nm as shown by a solid line in Fig.2. The electron-heavy hole (e-hh) absorption in the MQW region produces the sharp long-wavelength cutoff at 352 nm and the band-to-band absorption of the $Al_{0.35}Ga_{0.65}N$ buffer layer introduces the sharp short-wavelength cutoff at 297 nm. By changing Al components of $Al_xGa_{1-x}N$ barrier materials, and

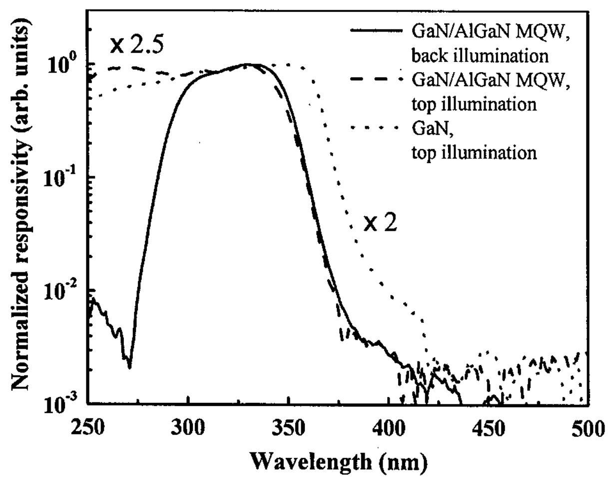

Fig.2 Spectral response curves of the MQW-based sample for back side (solid line) and top side (dashed line) illumination, and the control GaN sample for top side illumination (dotted line). All curves are normalized to the peak responsivity of the back-illuminated MQW detector.

the $Al_yGa_{1-y}N$ buffer layer materials, the long and short detection cut-off wavelengths, and the width of the narrow detection band can be tuned.[1] The signal-to-noise ratio is up to 10^3. The peak responsivity is 0.03 A/W at 330 nm. The photocurrent was found to increase linearly with the optical power as measured at 330 nm. In order to provide a qualitative comparison with the performance of the back-illuminated MQW detector, the spectral response curves of this sample and a control GaN bulk sample for top side illumination are also shown in Fig.2 by the dotted and the dashed lines, respectively.

The temporal response of the back-illuminated MQW detector was measured across a resistive load in series. Although the responsivity is only 0.007 A/W at 355 nm, the photocurrent decay as an exponential function of time was clearly observed after a 30 ps laser excitation at 355 nm. Fig.3(a) shows the exponential decay of the photocurrent across a 560 Ω load. The decay time constant as a function of the load resistance is plotted in Fig.3(b).[1] The linear relationship between the response time and the load resistance indicates the response time is RC limited. The time constant goes down to 5 μs at a load resistance of 50 Ω.

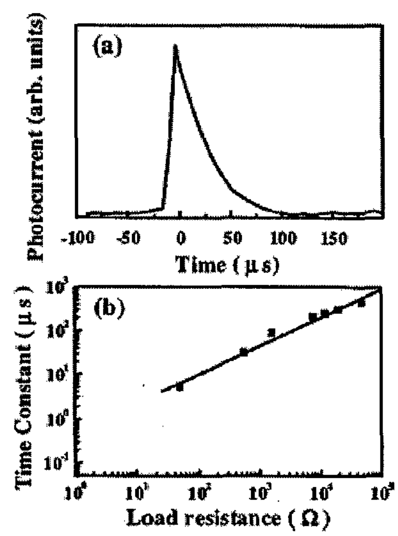

Fig.3 (a) Photocurrent as a function of time at a 560 Ω load after a 30 ps laser pulse excitation at 355 nm; and (b) response time as a function of the load resistance for the GaN/AlGaN MQW photodetector.

The results clearly show that a narrow spectral band detection and a fast response speed were achieved from the lateral-geometry back-illuminated GaN/AlGaN MQW UV photodetectors. To the best of our knowledge, this was the first demonstration of GaN/AlGaN MQW photodetectors.

3. Investigation of high internal gains for back-illuminated GaN/AlGaN heterojunction UV photodetectors

A GaN/AlGaN heterojunction UV photodetector consisting of a 0.2 μm GaN layer on a 0.7 μm $Al_{0.18}Ga_{0.82}N$ layer deposited on a c-plane sapphire substrate was fabricated. All layers are unintentionally doped. Gold metal stripes with width of 1 mm and spacing of 0.8 mm were produced by evaporating gold in vacuum on the GaN surface to form Schottky contacts.[2]

The spectral responsivity of the GaN/AlGaN heterojunction UV photodetector was measured using lock-in technique at a chopper frequency of 55 Hz and under a bias of 10 V, and the result is shown in Fig.4. The profile gives a narrow band pass spectral response between 365 nm and 343 nm. The sharp long- and short- wavelength cutoffs result from band-to-band absorption of the GaN layer and the $Al_{0.18}Ga_{0.82}N$ layer, respectively.[2] The responsivity is found

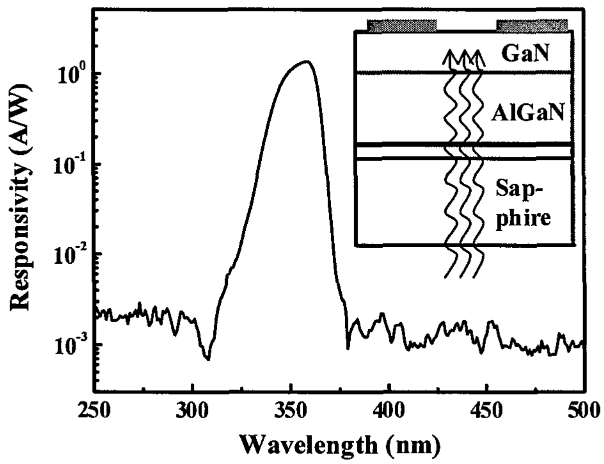

Fig. 4 Spectral response of the $GaN/Al_{0.18}Ga_{0.82}N$ detector measured under 10 V bias at the chopper frequency of 55 Hz. The inset shows schematic structure of the back-illuminated $GaN/Al_{0.18}Ga_{0.82}N$ photodetector.

to be dependent on chopper frequency because the decay time of photocurrent is comparable to the transit time for the chopper edge passing across the light beam (on the order of ms). The maximum responsivity is 1.35 A/W at 359 nm, corresponding to an apparent external quantum efficiency of 470%, which indicates the existence of internal gain of the photocurrent.

When operating in dc mode, the internal gain becomes much higher. Fig.5 shows the responsivity of the detector as a function of applied bias measured under 350 nm illumination

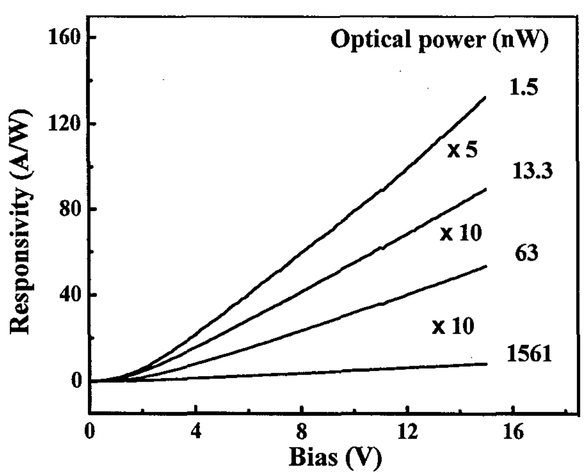

Fig.5 Responsivity as a function of bias measured by 350 nm illumination with different optical powers.

with different optical powers. It can be seen that the responsivity increases linearly with the increasing of the bias starting from 3 V. The responsivity increases much faster under weak power excitation. The responsivity goes up to 133 A/W at 15 V under 1.5 nW excitation, corresponding to an internal gain on the order of 10^3. Under biases above 15 V, the plot in Fig.5

predicts a potential of achieving much higher responsivity. [2] Unlike some photodetectors using GaN on Si (111),[9,10] no saturation was observed under voltages up to 15 V.

The extraordinary high internal gains with weak light illuminating show the unique advantage of this type of device to detect weak UV light signals. This breakthrough achievement of the high internal gain on GaN/AlGaN photodetectors was reported as a "Newsbreak" on page 15 in the February, 2003 issue of Laser Focus World.

4. Investigation of barrier-thickness dependence of photo-responsivity of perpendicular-geometry GaN/AlGaN MQW Schottky UV photodetectors

Three perpendicular-geometry GaN/AlGaN MQW Schottky UV photodetector samples namely svt1171, svt1172 and svt1174 with different barrier thickness and same well thickness were fabricated and investigate to study the barrier-thickness dependence of their photo-responsivity. The typical layer structure and photograph of these samples were shown in Fig.6. The active region of the three detectors consists of a 21 periods of GaN/AlGaN MQWs with 4 nm well thickness. The thickness of barriers was varied as 7 nm, 5 nm and 3 nm for svt1171, svt1172 and svt1174, respectively. The growth sequence was initiated from a 40 nm AlN and 1 µm Si-doped AlGaN buffer layer, and was finished by growing a thin AlGaN cap layer. Ti/Al/Ti/Au was evaporated to the etched part to form ohmic contacts, and Ni/Au composite was used for the Schottky contacts with a circular pattern on front side of the wafer, with an area of 0.03 mm^2 of each cell. To the best of our knowledge, this was the first attempt of producing Schottky type GaN/AlGaN MQW photodetectors with a perpendicular geometry. [3,4]

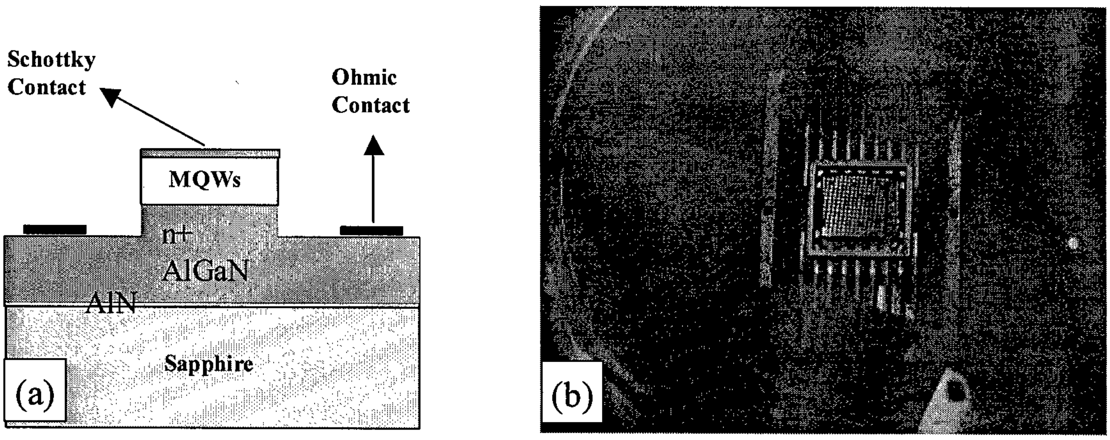

Fig.6 (a): Schematic diagram of semiconductor layer structure of a Schottky MQW photodetector; and (b) Photograph of detector array taken from svt1171 with a well thickness of 4 nm and a barrier thickness of 7 nm.

The photoresponse of the three GaN/AlGan MQW photodetectors were investigated and the barrier dependence of their photoresponsivity was studied. Fig.7(a) shows the spectral response curves of the three samples under zero bias and with back-side illumination. All curves give a band pass response between 300 nm and 360 nm. As the barrier thickness decreases, the responsivity rapidly increases in the active wavelength range. This is attributed to the enhanced probability of carrier tunneling through the barriers in the GaN/AlGaN MQW region. [3,4]

The performance of the three types of detectors was also tested under different biases. The spectral response curves for sample svt1174 (with a well thickness of 4 nm and a barrier thickness of 3 nm) as a function of bias are shown in Fig.7(b) with biases up to 5 V. The inset shows responsivity as a function of applied bias for the three samples under 350 nm illumination. The responsivity goes up with the increasing of the applied bias and saturates at around 3 V. This indicates that large electric fields can sweep out photo-generated carriers more efficiently from the active MQW region, and almost all carriers can be transported to the collectors after a certain field is reached.[3,4] The fields not only speed up the carrier drift but also assist carriers of tunneling through the barriers.

The internal quantum efficiencies of svt1174 under biases larger than 3 V are close to 100% by taking advantage of tunneling Schottky MQW detectors.

The results indicate that to increase photoresponsivity of the GaN/AlGaN MQW UV photodetectors, a thin barrier thickness (such as 3 nm), and a larger applied bias (such as 3 V) should be considered.

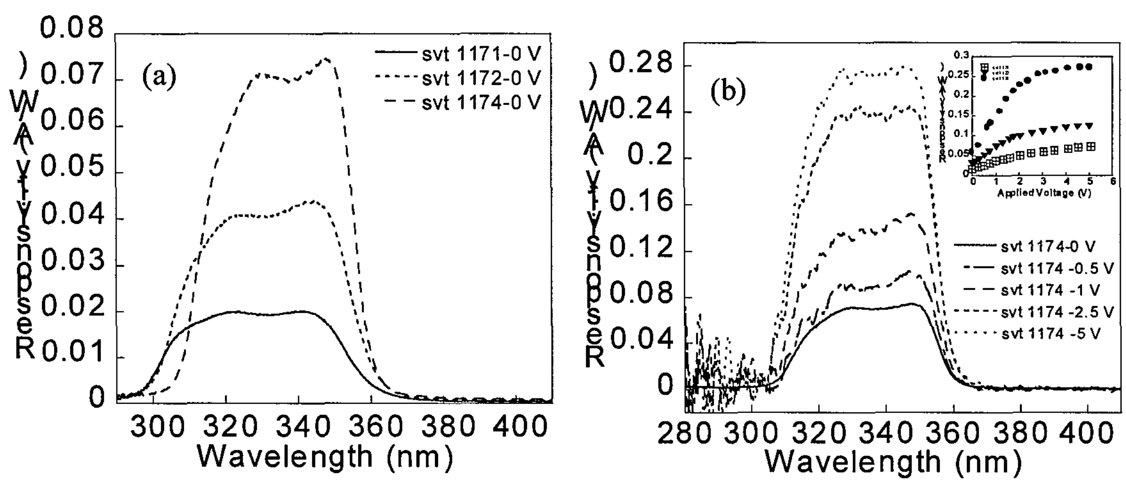

Fig.7 (a) Spectral photoresponse curves of the three Schottky MQW UV detectors with different QW barrier widths under zero bias; and (b) Spectral photoresponse curves of svt1174 under different biases. The inset shows responsivity as a function of bias for the three samples with 350 nm illumination.

5. Fabrication and investigation of UV photodetectors using SiC as a p-type layer and a substrate

There are two major problems for making high quality p-i-n GaN/AlGaN photodetectors with sapphire substrate. The first difficulty is the p-type doping in AlGaN materials. The commonly used dopant for p-type doping, magnesium (Mg) does not have expected electrical activity to provide high concentration holes to valence band. The activation energy is about 190 meV in GaN material and much higher in AlGaN materials. It is difficult to achieve low

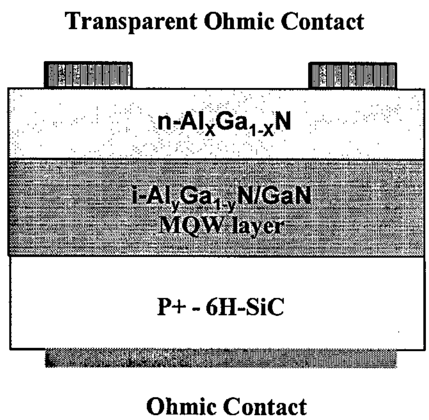

Fig.8 Schematic diagram of the device configuration of UV photodetector consisting of 6H SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n) structure.

resistivity in p-type AlGaN materials, which is essential for transporting photogenerated carriers in photodetectors.

The second difficulty is the growth of high quality AlGaN materials on normally used (0001) sapphire substrates. The lattice mismatch between (0001) sapphire and GaN is as high as 15%, which leads to high density of dislocations in AlGaN layers deposited on sapphire. To solve this problem, GaN bulk materials and 6H-SiC materials are suggested as substrates for AlGaN growth. As a native substrate, GaN bulk material is the best candidate but at present time large pieces of GaN are not available.

To overcome these two difficulties of low p-type doping level and poor quality of AlGaN epitaxy layers on sapphire substrates, we have designed, fabricated and tested GaN/AlGaN photodetector structures using p-type 6H-SiC as a p-type layers in p-i-n structures as well as a substrate for the growth of AlGaN layers, where the p-i-n structures for UV photodetectors will be 6H-SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n).

Fig.8 shows the schematic diagram of layer structures of these 6H-SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n) photodetectors.[5] The detector is designed for front side illumination. These photodetectors have the following innovations and advantages:

a) P-type 6H-SiC has very good conductivity and can provide efficient hole collection in photodetectors. P-type doping in AlGaN materials can be avoided.

b) Growth of high quality AlGaN materials is expected. The lattice constants of GaN, AlN and 6H-SiC are 3.189 Å, 3.112 Å and 3.08 Å, respectively. The lattice mismatch between them is less than 3%, which makes 6H-SiC the best lattice-matched substrate among the currently available hetero-substrates (6H-SiC, Sapphire, ZnO, Si, GaAs, 3C-SiC, and MgO). This is

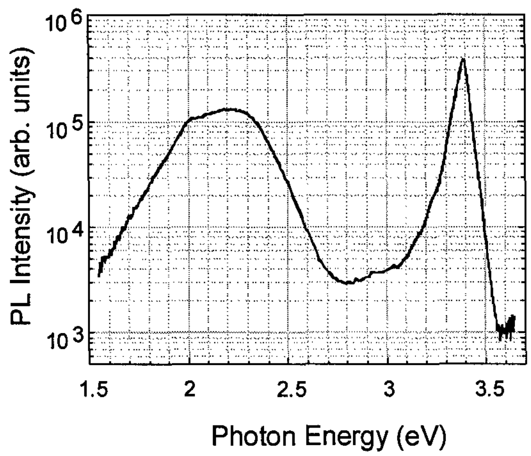

Fig.9 PL spectroscopy of the 6H SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n) structure.

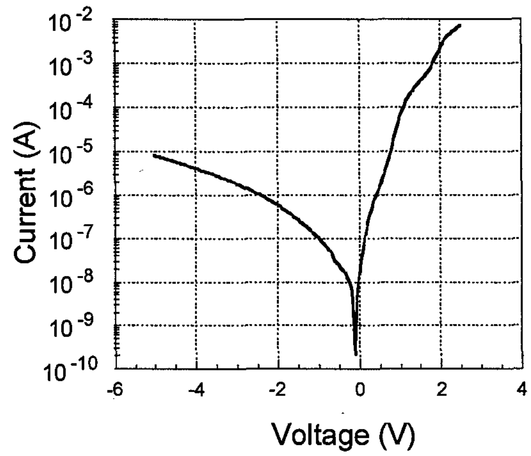

Fig.10 I-V curve of the 6H SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n) detector.

important in developing solar blind photodetectors which require AlGaN alloys with high Al fractions and less defects;

c) P-type ohmic contacts can be easily made by directly evaporating metal alloys on the backside of 6H-SiC substrate and no etch process is required. This makes device fabrication rather simple.

As our first attempt to develop UV photodetectors based on 6H-SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n) structures, GaN (4 nm)/$Al_{0.27}Ga_{0.73}N$ (5 nm) MQWs with 30 periods were deposited by MBE on a p^+-6H-SiC substrate. A 0.4 μm n^+-$Al_{0.25}Ga_{0.75}N$ layer was grown on the top to act as a n-type conducting layer as well as a window layer. Ohmic contacts were made on both top and backsides as illustrated in Fig.8.

Fig.9 shows a typical PL spectroscopy of the semiconductor layers in these devices measured at room temperature. The narrow peak located at 3.4 eV is from band to band transition in MQW region. It has a half width of only 63 meV at room temperature, which indicates the high quality of the MQW semiconductor layers.[5] The broad peak around 2.2 eV is so-called yellow luminescence and is from radiative recombination of deep centers in GaN.

Current-voltage curve for this device is shown in Fig.10. Near zero bias, the dark current is as low as 10^{-10} A. However, it increases rapidly with increasing of the reverse bias. This negative feature results from high auto-doping level in GaN/AlGaN MQWs.[5]

By illuminating the device from the front side, the spectral response was recorded at room

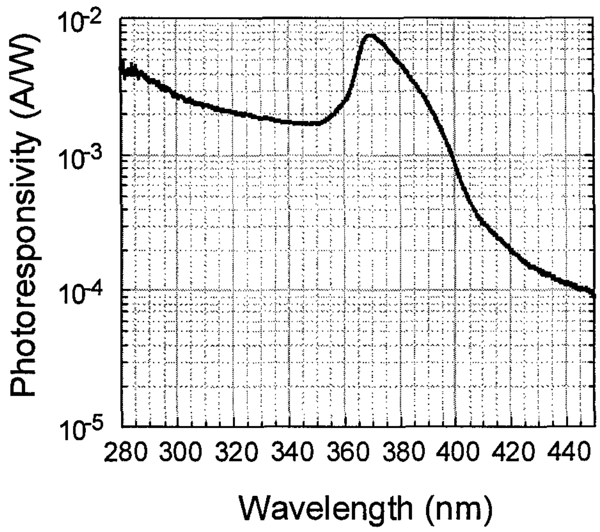

Fig.11 Spectral response of the 6H SiC (p) – GaN/AlGaN MQWs (i) – AlGaN (n) photodetector.

temperature in the UV wavelength range from 280 nm to 450 nm. The result is presented in Fig. 11.[5] This demonstrates that SiC-based GaN/AlGaN MQW photodetectors operates successfully. The photoresponse is induced by photon absorption of the MQW layers. The responsivity will be greatly increased if the auto-doping problem in the MQWs is solved.

6. Fabrication and investigation of GaN/AlGaN MQW UV photodetectors with SiN dislocation-blocking layers

In order to reduce dark current and improve photodetector performance, a number of GaN/AlGaN p-i-n detector strusctures were grown with SiN dislocation-blocking layers in VCU's modified rotating disc MOCVD system. A typical sample structure is shown in Fig.12. The growth was initiated on AlN buffer layers grown by molecular beam epitaxy (MBE) on c-plane sapphire (α-Al_2O_3). Trimethylgallium (TMG), trimethyl-aluminum (TMAl), Trimethylindium (TMIn), and ammonia (NH3) were used as sources of Ga, Al, In, and N, respectively. Silane and Cp_2Mg were the dopant sources of Si and Mg for n-type and p-type, respectively. All detector structures involve thick (~ 2.5 μm) n-$Al_xGa_{1-x}N$ absorption layers grown on AlN buffer layers. In/Si co-doping is used to obtain n-type behavior. After an

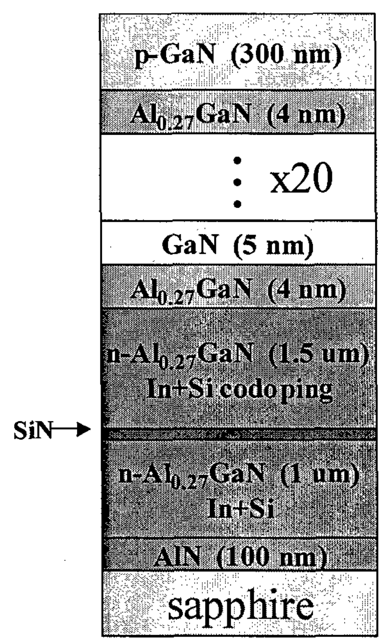

Fig.12 Sample structure of newly grown GaN/AlGaN MQW photodetectors with SiN dislocation-blocking layer.

AlGaN thickness of 0.5-1 μm, a thin layer of SiN film is deposited and the thermal etching of SiN and AlGaN under the flowing gas of H_2 and NH_3 is performed. This SiN layer is expected to partially block the threading dislocations that result in large leakage current. Then, another 1-1.5 μm n-AlGaN layer is deposited. This layer is followed by the growth of the 10-20 periods AlGaN/GaN MQW active region, and finally, a top layer of p-GaN. [6]

After the activation of Mg dopants in p-GaN, the 300 μm-size devices were fabricated using Ti/Al/Ti/Au and Ni/Au alloys for n- and p-type contacts, respectively. Ohmic contacts were achieved after annealing at 650° C for 1 minute. The devices were wire-bonded after the deposition of a 150 nm thick Au overlayer on both n-type and p-type contacts.

Fig.13 shows the I-V characteristics of a photodetector device that was grown using the SiN deposition. The dark current is as low as ~ 1×10^{-13} A at zero bias. It is only 2×10^{-12} A even at –5 V. The dark current density is only $3 \times 10^{-10} \sim 6 \times 10^{-9}$ A/cm^2 in the bias range of 0 ~ -5 V. This extremely low dark current is attributed to successful blocking of threading dislocations by SiN layer. Other attempt to reduce dark current of GaN photodetectors is to use low-temperature grown GaN cap layer. Lee *et. al.* have made GaN photodetectors by this method and have reduced dark current density to $10^{-9} \sim 10^{-6}$ A/cm^2 in the bias range of 0 ~ -5 V. It can be seen that the dark current reported here is much lower than that of devices using low-temperature grown GaN cap layer.

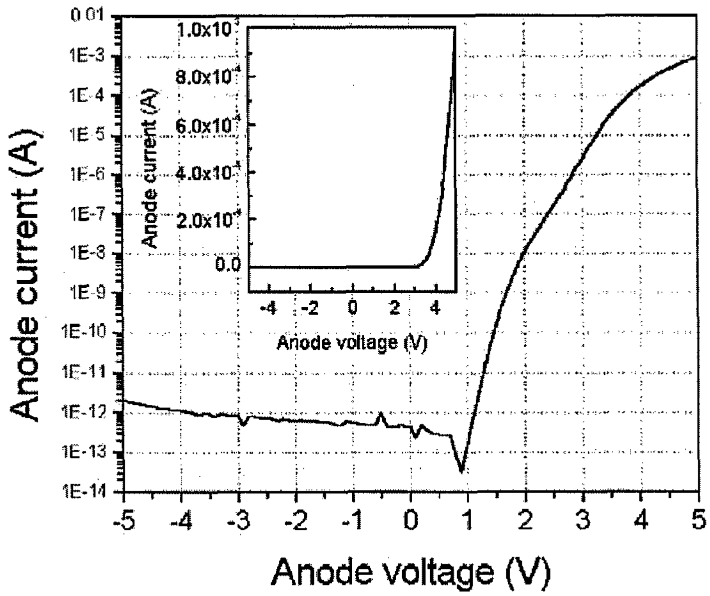

Fig.13 I-V characteristics of an GaN/AlGaN MQW detector grown after the SiN deposition in order to reduce the threading dislocations. The inset shows the same data in linear scale.

The samples were then mounted on a probe station and photoresponse measurements were performed using a UV enhanced Xe-Lamp monochromator system for optical excitation. Responsivities of these MOCVD grown samples are observed to be higher than that of the previous samples grown completely by MBE. Fig.14 displays spectral response of the photodetector with a structure shown in Fig.12. The peak response is at 340 nm. It can be seen that the deposition of SiN does not distort the spectral response curve.[6]

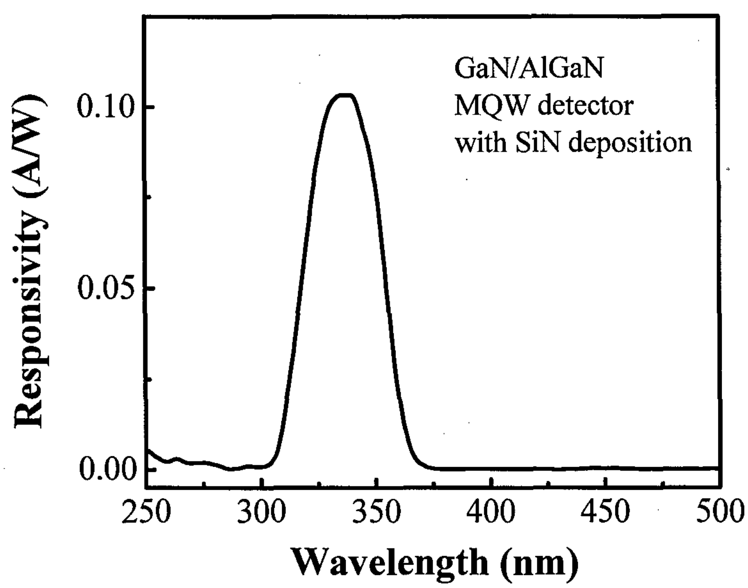

Fig.14 Spectral photoresponse of GaN/AlGaN MQW detectors with SiN deposition.

It is clear that deposition of SiN dislocation-blocking layer is helpful in improving performance of GaN/AlGaN photodetectors.

7. Investigation of sequential resonant tunneling in p-GaN/i-MQW/n-AlGaN UV photodetectors

In order to achieve high quantum efficiency and fast response speed, we have fabricated and investigated p-GaN/i-MQW/n-AlGaN UV photodetector structures with a possible sequential resonant tunneling (SRT) under proper biases.[6,7]

With undoped GaN/AlGaN MQWs embedded in p-n junction, the linear potential profile across the MQW active region makes sequential resonant tunneling of photogenerated carriers realizable. Since electrons will be transported on a time scale of picoseconds, a MQW photodetector working in SRT condition expects to have high efficiency and high response speed.[7] SRT is generally represented by current peaks in I-V curves of a p-i(MQW)-n diode. However, due to large leakage current in GaN/AlGaN system, SRT has not been experimentally observed in GaN/AlGaN MQWs in the past.

Due to the low leakage of our newly grown GaN/AlGaN MQW photodetectors with SiN dislocation-blocking layers as shown in Fig.12, sequential resonant tunneling at room temperature was observed by measuring I-V curve for the first time.[6] The photodetector used for SRT experiments has a similar material structure to that shown in Fig.12 but has different growth process. The photodetector consists of 20 periods GaN(5 nm)/$Al_{0.27}Ga_{0.73}N$(4nm) QWs. The effective contact area is about 0.1 mm^2. This device was originally designed to have SRT around -5 V.

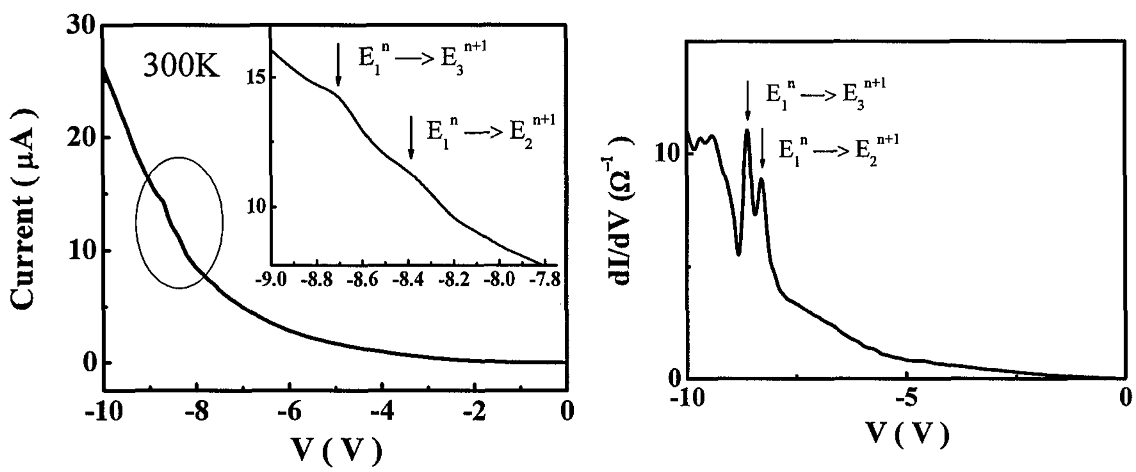

Fig. 16 (a) I-V curve of GaN/AlGaN photodetector sample 21A with SiN deposition. Two peaks are shown at –8.36 V and –8.70 V. The inset shows the enlarged I-V curve near the current peaks. (b) dI/dV curve obtained from the I-V curve shown in the left figure.

The I-V curve was measured in the bias range from 0 to –10 V at room temperature and is shown in Fig.16 (a) and the corresponding dI/dV curve is shown in Fig.16 (b). Two current peaks are observed at –8.36 V and –8.70 V, respectively. The inset in Fig.16 shows the enlarged I-V curve near these peaks. We refer the peak at –8.36 V to resonant tunneling of electrons from the ground state E_1 of a well to the first excited state E_2 of an adjacent well, and the peak at –8.7 V to resonant tunneling of electrons from the ground state E_1 of a well to the second excited state E_3 of an adjacent well in the GaN/AlGaN MQW structure. Fig.17 shows the alignment of these energy states in SRT conditions for $E_1^n \rightarrow E_2^{n+1}$ (upper) and $E_1^n \rightarrow E_3^{n+1}$ (lower). [7]

The current-voltage experiments shown in Fig.16 were done at room temperature. To get more pronounceable evidence of SRT, the I-V and photocurrent measurements at low temperatures down to ~ 10K are planned and will be done under the future support.

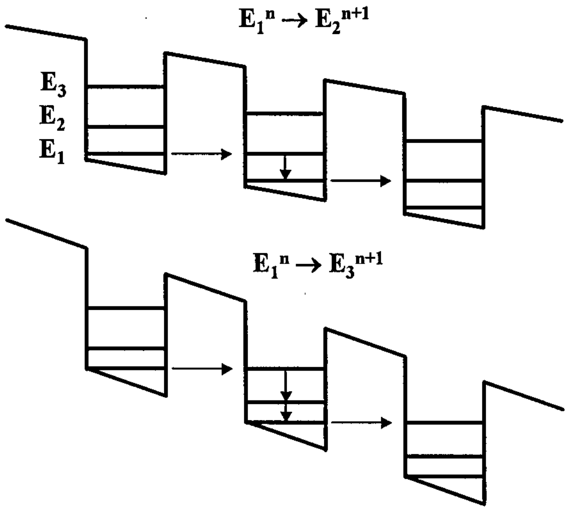

Fig.17 Band alignment of electron energy states in SRT conditions for $E_1^n \rightarrow E_2^{n+1}$ (upper) and $E_1^n \rightarrow E_3^{n+1}$ (lower).

8. Investigation of deep-center and shallow-donor recombination in GaN/AlGaN MQW photodetectors

Deep centers in III-Nitride materials play an important role in the performance of III-Nitride photovoltaic devices. They produce persistent photocurrent and greatly decrease the response speed of III-Nitride-based photodetectors. In addition, the centers are in part responsible for reduced quantum efficiency in injection lasers and light emitting diodes based on III-Nitrides. On the other hand, these deep centers are responsible for the high gain in some III-Nitride photodetectors.

Photocapacitance study is an ideal method to investigate deep centers. One assumption in conventional photocapacitance model is that all carriers at defect levels will eventually emit out to the band edge thus leading to a constant saturation photo-capacitance (ΔC_0). However, our research on a Schottky diode of GaN/AlGaN MQWs indicates that the saturation photocapacitance depends strongly on the optical excitation power. Our transient photocapacitance (TPC) experiments show that the magnitude of saturation photocapacitance is linearly dependent on the square root of optical excitation power, instead of remaining constant. This indicates the effects of defects in GaN are different from that of other semoconductor materials and the conventional model cannot account for the impact of defects on performance of GaN photovoltaic devices.

We have studied a new photocapacitance model to explain the optical power dependence of

TPC traces measured in a GaN/AlGaN MQW Schottky diode. In comparison with the experimental results, deep-level and shallow-donor pairs are found to be responsible to the observed unusual photocapacitance phenomena as well as the long response time of the photodetectors.

Fig.18 shows a schematic band diagram of a Schottky diode (n-type semiconductor). The assumptions are that there are one deep level E_t and one shallow level E_t' below the conduction band. The dashed line in Fig.18 indicates the position of the Fermi level, and the solid dots represent electrons at different levels. Under a continuous light excitation, electrons at the deep level will be excited to the conduction band (arrow #1). The re-capturing process from the conduction band to the deep level can be ignored since the capture cross-section is very small for such a deep level. Most of electrons on the conduction band will be swept out from the space-charge region by the Schottky induced field (arrow #2). A fraction of photo-ionized electrons will be re-captured by the shallow level (arrow #3) that is above the Fermi level in the space-charge region and is empty in this region. The electrons at the shallow level will recombine with holes at the deep level (arrow #4).[8]

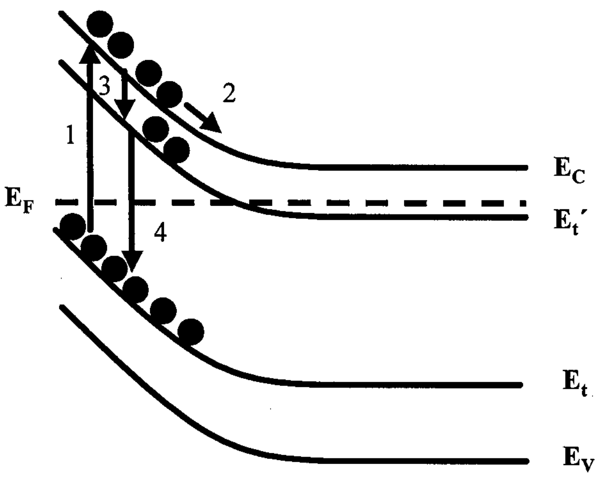

Fig.18 Schematic band diagram of a n-type Schottky diode with a shallow level E_t' and a deep level E_t in the band gap under optical excitation. The arrows indicate electron photoionization at E_t (arrow 1), electron transport on the conduction band (arrow 2), electron re-capturing by E_t' (arrow 3) and E_t' to E_t recombination (arrow 4).

Our transient photocapacitance model is deduced based on capture and emission of electrons on the deep level Et and shallow donor Et'. Assuming that the density of electrons at the deep level is n_t at time t and the concentration of the deep level centers is N_T, the rate equation of electron population for the photoionization and re-capture at the deep level is written as

$$\frac{dn_t}{dt} = -e_n n_t + r(N_T - n_t)\alpha(N_T - n_t), \tag{1}$$

where r is recombination coefficient for electrons at the shallow level recombining with holes at the deep level, α is a proportionality constant and e_n is emission rate of electrons from the deep level, $e_n = \frac{1}{\tau} = \phi\sigma$. The first item of the right side of Eq. (1) represents reduction of electrons at the deep level due to photoionization while the second item represents increment of electrons due to re-capturing from the shallow level.

Considering the initial condition at $t = 0$, $N_t - n_t = 0$, the solution for Eq. (1) is

$$N_T - n_t(t) = A_1 \frac{1 - A_2 e^{-A_3 t}}{1 + A_2 e^{-A_3 t}} - A_4, \tag{2}$$

where $A_4 = \frac{e_n}{2r\alpha}$, $A_1 = \sqrt{A_4^2 + 2A_4 N_T}$, $A_3 = 2r\alpha A_1$, and $A_2 = \frac{A_1 - A_4}{A_1 + A_4}$.

The expression for the transient photocapacitance, *ΔC(t),* is derived as

$$\Delta C(t) = \Delta C_0 [1 - \frac{2A_1 A_2}{(A_1 - A_4)(1 + A_2 e^{-A_3 t})} e^{-A_3 t}]. \tag{3}$$

The saturation photocapacitance, ΔC_0, which is the total capacitance change at $t = \infty$, can be expressed as

$$\Delta C_0 = \frac{(1-\alpha)C(N_T - n_{t0})}{2N_D} \approx \frac{(1-\alpha)C}{2N_D} (\frac{e_n N_T}{r\alpha})^{\frac{1}{2}}. \tag{4}$$

Substituting $e_n = \phi\sigma = \frac{P\sigma}{Sh\nu}$ into the Eq (4), the power dependence of the saturation photocapacitance $\Delta C_0(P)$ is obtained as

$$\Delta C_0(P) \approx \frac{(1-\alpha)C}{2N_D} (\frac{\sigma N_T}{r\alpha Sh\nu})^{\frac{1}{2}} P^{\frac{1}{2}}, \tag{5}$$

where P is the optical excitation power, S is the device area, h is Plank constant and ν is the frequency of the incident light. The above equation predicts a linear relationship between the saturation photocapacitance and the square root of the optical power under weak excitation.

From Eq. (3), it can be seen that A_3 represents the effective emission rate of electrons e_n'. The power dependence of the effective emission rate is deduced to be

$$e_n' = A_3 = \sqrt{e_n^2 + 4r\alpha N_T e_n} = \sqrt{(\frac{\sigma}{Sh\nu})^2 P^2 + \frac{4r\alpha\sigma N_T}{Sh\nu} P}, \tag{6}$$

where $e_n = \phi\sigma = \frac{P\sigma}{Sh\nu}$ is used.

The theoretical predictions shown above are used to fit the experimental data of photocapacitance measured on GaN/AlGaN MQW photodetectors, and are found to be highly coincident with the experimental results. This indicates that the deep-level and shallow-donor pairs are responsible for the slow response of these photodetectors.

The transient photocapacitance measurements were performed on a GaN/AlGaN MQW photodetector at room temperature. Under 450 nm light excitation, transient photocapacitance traces for different optical excitation power levels were recorded and are shown by scatter symbols in Fig.19.[8] It can be clearly seen that the transient photocapacitance saturates at different levels for different optical powers. This phenomenon cannot be explained by the conventional photocapacitance model. The TPC traces, however, can be fitted using Eq.(3), which is deduced within the framework of the proposed model. The solid lines in Fig.19 show the fit. It can be seen that calculations agree very well with the experimental data.

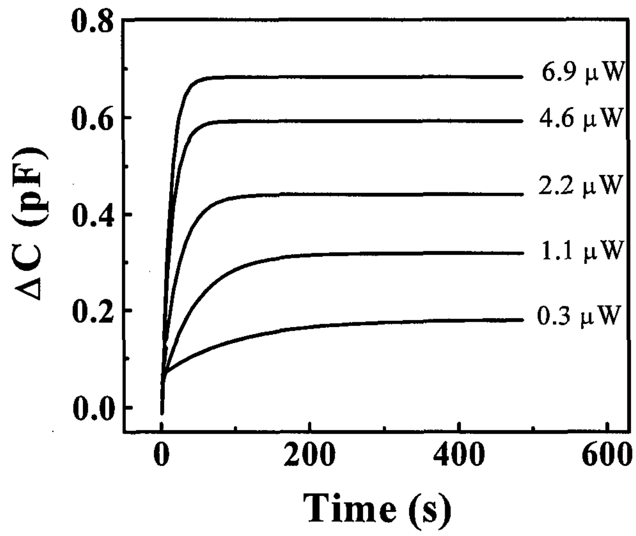

Fig.19 Transient photocapacitance (TPC) traces of the GaN/AlGaN MQW Schottky diode measured at 450 nm with different optical excitation powers (scatter symbols), and corresponding fitting curves of TPC simulated by the theoretical expression of TPC Eq.(15) (solid lines).

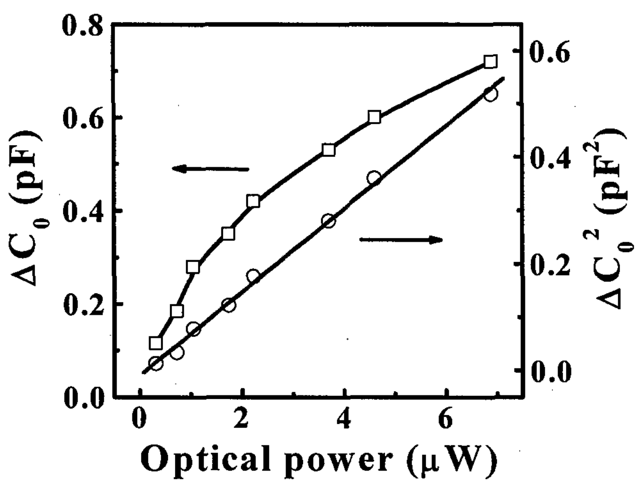

Fig.20 Experimental plots of saturation photocapacitance ΔC_0 (squares) and square of the saturation photocapacitance ΔC_0^2 (circles) as functions of optical excitation power. The straight line shows a linear fitting to the experimental $\Delta C_0^2 \sim P$ relationship.

The saturated photo-capacitance ΔC_0 is plotted as a function of the optical excitation power P with square symbols in Fig.20.[8] When the optical power increases from 0.31 μW to 6.9 μW, the saturated photocapacitance increases from 0.12 pF to 0.72 pF. $\Delta C_0^2 \sim P$ relationship is plotted in Fig.20 by the circles. With a correlation coefficient of 0.999, $\Delta C_0^2 \sim P$ shows a well-defined linear relationship, which is consistent with the model predictions described by Eq.(5).

The effective emission rate e_n', which is the parameter A_3 in Eq.(3) used for fitting TPC traces, is shown as a function of excitation power P in Fig.21 by open circles. The expression of e_n', Eq.(6), was used to fit the $e_n' \sim P$ relationship. The fitting result, as shown by the solid line in Fig.21, follows the $e_n' \sim P$ data well.

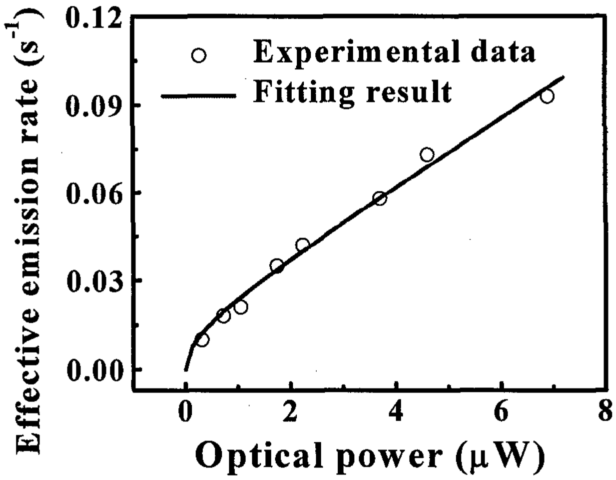

Fig.21 Effective emission rate (circles) as a function of optical excitation power and non-linear fitting result (solid line) according to Eq. (6).

The assumption of shallow-donor and deep-center recombination in the model is reasonable for GaN. In fact, various shallow-donor and deep-center recombinations have been widely reported to be the origin of the yellow, green and blue luminescence in GaN.[11-14] Our investigations indicate that the shallow-donor and deep-center recombination is also responsible for the observed unusual photocapacitance phenomena. Since the photocapacitance response is related to the photovoltage response, the deep-level and shallow-donor pairs are responsible for the slow response of GaN/AlGaN MQW photodetectors as well.

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Dr. S. K. Zhang, Senior Research Associate, Project Leader
Dr. G. Comanescu, Research Associate
Mr. F. Zeng, Research Associate
Mr. I. Shtau, Master graduate student
Mr. S. Gundry, Undergraduate student (graduated in 2004)

Publications:

1. S. K. Zhang, W. B. Wang, H. Morkoc and R. R. Alfano, "Unusual transient photocapacitance in GaN/AlGaN multi-quantum wells", Superlattices and Microstructures, 35, 77-84 (2004).
2. A. Teke, S. Dogan, F. Yun, M. A. Reschikov, L. He, X. Q. Liu, H. Morkoc, S. K. Zhang, W. B. Wang, and R. R. Alfano, "GaN/AlGaN back-illumination multiple-quantum-well Schottky barrier ultraviolet photodetectors", Solid State Electronics, 47, 1401-1408 (2003).

3. A. Teke, S. Dogan, H. Le, D. Huang, F. Yun, M. Mikkelson, H. Morkoc, S. K. Zhang, W. B. Wang, and R. R. Alfano, "p-GaN i-GaN/AlGaN multiple-quantum-well n-AlGaN back-illuminated ultraviolet detectors", Journal of Electronic Materials, 32, 307-311 (2003).

4. S. K. Zhang, W. B. Wang, F. Yun, L. He, H. Morkoc, X. Zhou, M. Tamargo and R. R. Alfano, "Back-illuminated ultraviolet photodetector based on GaN/AlGaN multiple quantum wells", Appl. Phys. Lett., 81, 4628 (2002).

5. S. K. Zhang, W. B. Wang, I. Shtau, F. Yun, L. He, H. Morkoc, X. Zhou, M. Tamargo and R. R. Alfano, "Back-illuminated GaN/AlGaN heterojunction UV photodetector with high internal gain", Appl. Phys. Lett., 81, 4862 (2002).

Presentations

1. S. K. Zhang, W. B. Wang, and R. R. Alfano, "Avalanche AlGaN light-emitting diode", presented at "the AFOSR Workshop on Nanoscale Issues Nitride Semiconductors", Anchorage, Alaska, August 22~25, 2004.

2. S. K. Zhang, W. B. Wang, A. Teke, M. Reshchikov, L. He. S. Dogan, F. Yun, H. Morkoc, and R. R. Alfano, "Photoionization cross sections of deep centers in GaN/AlGaN MQW detectors", presented in the 8th Wide Bandgap III-Nitride Workshop, Richmond, Virginia, on September 28–October 1, 2003.

3. S. K. Zhang, W. B. Wang, F. Yun, L. He, H. Morkoc, X. Zhou, M. Tamargo, and R. R. Alfano, "Ultraviolet photodetectors based on GaN/AlGaN", presented in the 2003 AFOSR Semiconductor Detectors Program Review Meeting, Anaheim, CA, on January 8-9, 2003.

4. S. K. Zhang, W. B. Wang, F. Yun, L. He, H. Morkoc, X. Zhou, M. Tamargo, and R. R. Alfano, "Tunable high efficiency resonant tunneling GaN/AlGaN multiple quantum wells ultraviolet photodetectors", presented in the GaN Photodetector Conference, Richmond, Virginia, on March 11-14, 2002.

5. S. K. Zhang, W. B. Wang, F. Zeng, I. Shtau, and R. R. Alfano, "Tunable high efficiency sequential resonant tunneling GaN/AlGaN multiple quantum wells UV photodetectors", presented in the Symposium of Frontiers of Photonics, New York, NY, on November 5, 2001.

6. S. K. Zhang, W. B. Wang, F. Yun, H. Morkoc and R. R. Alfano, "Tunable high efficiency resonant tunneling GaN/AlGaN multiple quantum wells ultraviolet photodetectors", presented in the 2001 AFOSR Photodetector Program Review Meeting, Williamsburg, Virginia, on June 4-6, 2001.

New Discoveries / patents

1. R. R. Alfano, S. K. Zhang, and W. B. Wang, "Photodetectors and optically pumped emitters based on III-nitride multiple-quantum-well structures", a patent disclosure and provisional U. S. patent application filed on 12/02/2002 with No. 60/430,971, and U. S. patent application filed on 12/05/2003 with No. 10/728,562.

Honors/Awards

Our breakthrough achievement on high internal gain of the GaN/AlGaN heterojunction UV photodetectors was reported as a "Newsbreak" on page 15 in the February, 2003 issue of "Laser Focus World", entitled "Gallium nitride-based photodetector reaches a gain of 1000".

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5. Annual Progress Report for the third year (09/01/2002 – 08/31/2003) of the AFOSR grant #F49620-01-1-0188 submitted to AFOSR from CCNY on 9/9/2003.
6. Annual Progress Report for the fourth year (09/01/2003 – 08/31/2004) of the AFOSR grant #F49620-01-1-0188 submitted to AFOSR from CCNY on 12/21/2004.
7. R. R. Alfano, S. K. Zhang, and W. B. Wang, "Photodetectors and optically pumped emitters based on III-nitride multiple-quantum-well structures", a patent disclosure and provisional U. S. patent application filed on 12/02/2002 with No. 60/430,971, and U. S. patent application filed on 12/05/2003 with No. 10/728,562.
8. S. K. Zhang, W. B. Wang, H. Morkoc and R. R. Alfano, "Unusual transient photocapacitance in GaN/AlGaN multi-quantum wells", Superlattices and Microstructures, 35, 77-84 (2004).

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14. M. A. Reshchikov, M. Zafar Iqbal, H. Morkoc, S. S. Park, K. Y. Lee, Appl. Phys. Lett., 83, 266 (2003).

Appendix

The reprints of the following papers and a copy of the patent abstract produced from this AFOSR research project are attached:

1. S. K. Zhang, W. B. Wang, F. Yun, L. He, H. Morkoc, X. Zhou, M. Tamargo and R. R. Alfano, "Back-illuminated ultraviolet photodetector based on GaN/AlGaN multiple quantum wells", Appl. Phys. Lett., 81, 4628 (2002).
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4. A. Teke, S. Dogan, H. Le, D. Huang, F. Yun, M. Mikkelson, H. Morkoc, S. K. Zhang, W. B. Wang, and R. R. Alfano, "p-GaN i-GaN/AlGaN multiple-quantum-well n-AlGaN back-illuminated ultraviolet detectors", Journal of Electronic Materials, 32, 307-311 (2003).
5. S. K. Zhang, W. B. Wang, H. Morkoc and R. R. Alfano, "Unusual transient photocapacitance in GaN/AlGaN multi-quantum wells", Superlattices and Microstructures, 35, 77-84 (2004).
6. R. R. Alfano, S. K. Zhang, and W. B. Wang, "Photodetectors and optically pumped emitters based on III-nitride multiple-quantum-well structures", a patent disclosure and provisional U. S. patent application filed on 12/02/2002 with No. 60/430,971, and U. S. patent application filed on 12/05/2003 with No. 10/728,562.